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Thermal Simulation of a Diode Module Cooled with Forced Convection

by Gregory K. Ovrebo

ARL-MR-0787 July 2011

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14. ABSTRACT

We have performed a thermal simulation of an electronic module cooled by forced convection and compared the simulation to the results of a laboratory test of the module. We modeled the module's geometry and materials, and used the operating conditions of the laboratory experiment as inputs for the simulation. We found close agreement between the steady-state temperatures calculated in our model and the temperatures observed in the laboratory, validating our simulation methods.

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Contents

List of Figures

1. Introduction

The U.S. Army Research Laboratory (ARL) is developing prototypes of electronic systems for Army applications requiring high voltages and operation at high temperatures. Silicon carbide (SiC) devices are well suited for such applications because of the wide bandgap of this semiconductor material and the ability of such devices to operate at high temperatures without significant changes in their operating specifications.

ARL has built a module with four SiC diodes for use in high-voltage power applications. This report describes our efforts to model, with computer simulations, a laboratory test of this module. We describe the three-dimensional (3-D) model of the diode module and the physical definition of the thermal simulation problem. We calculated peak temperatures in the SiC diodes, compared them to temperatures measured on the benchtop with a thermal imaging camera, and validated the reliability of our simulation methods.

2. Construction of a Model for Simulation

Figure 1 shows a photograph of the diode bridge circuit. Four SiC diodes are mounted on an aluminum nitride circuit board with direct-bonded copper lands and connected in a bridge circuit. The circuit board is mounted on a copper heat sink roughly 2 in square with 225 pin fins. In our lab test, the module was operated at a constant voltage for several minutes to allow the diodes to reach thermal equilibrium. The steady-state temperatures on the surface of the circuit board were then observed with a thermal imaging camera.

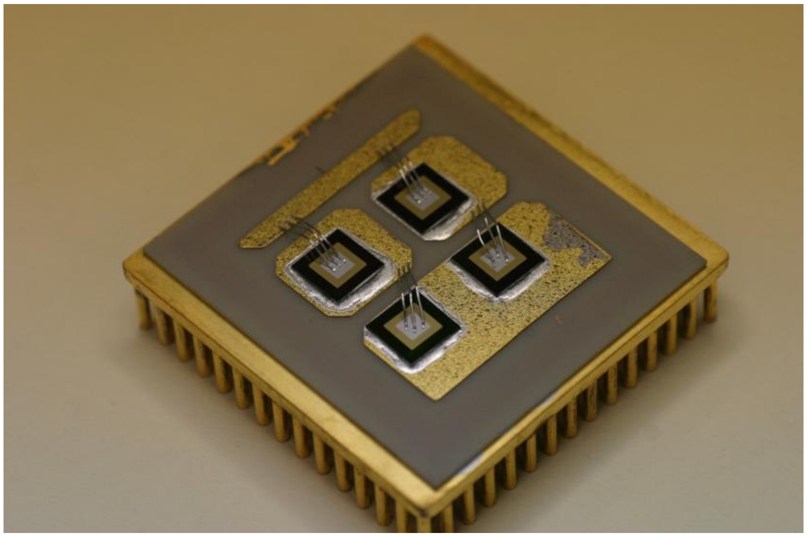

Figure 1. The four-diode bridge circuit board mounted on a pin-fin heat sink.

Figure 2 shows our 3-D model of the bridge module, prepared with Dassault Systemes' SolidWorks 3-D computer-aided design (CAD) software. The model was somewhat simplified compared to the physical module in order make the subsequent simulation easier. For instance, we omitted the bond wires between the diodes and the copper lands, a fine detail that would have increased the complexity of the calculation without adding much useful information on the thermal behavior of the circuit.

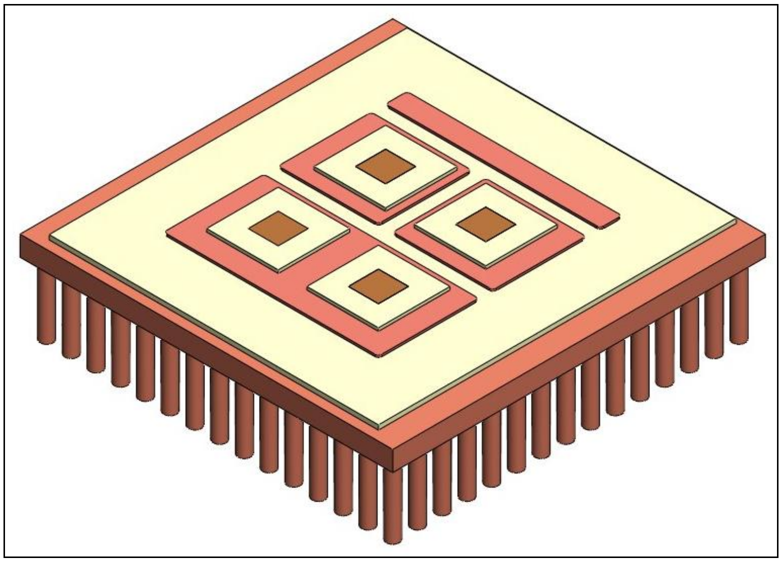

Figure 2. SolidWorks 3-D model of the four-diode module.

During the laboratory test of the module, each diode operated with a steady-state power dissipation of 7.6 W. A fan blew room-temperature air over the heat sink pins at a speed of 7.2 m/s. Figure 3 shows photographs of the circuit board in the laboratory test setup. The parameters of the laboratory test were incorporated into the definition of our thermal simulation. The simulation software we used was SolidWorks Simulation (formerly called CosmosWorks), a finite element analysis package that can perform thermal and fluid-flow calculations on 3-D models.

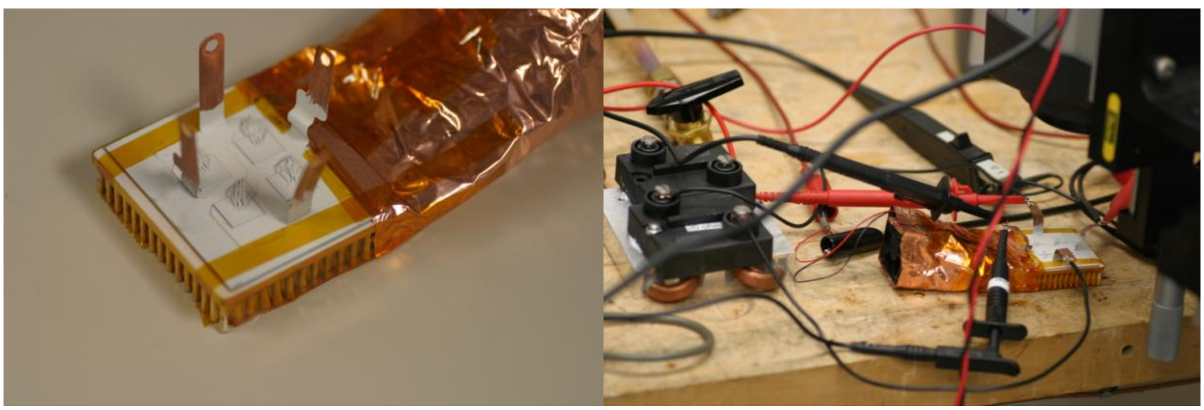

Figure 3. The four-diode board configured for thermal testing in ARL's laboratory.

3. Thermal and Flow Simulation

Our first attempt at configuring the simulation used what SolidWorks Simulation refers to as an external flow. Air is directed in a uniform flow over all external surfaces of the module, including the heat sink and the circuit board. The ambient air temperature and the initial temperature of the module were both defined to be 20 °C. With the energy deposition set at 7.6 W per device and the external air flow set at 7.2 m/s, we calculated a maximum temperature in the diodes of 86.02 °C. Figure 4 is a contour plot of the calculated temperature distribution on the top surface of the circuit board.

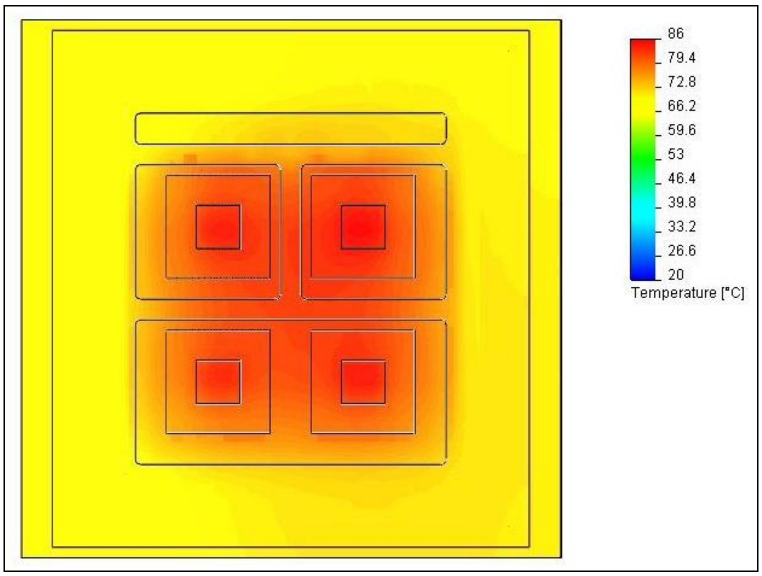

Figure 4. Temperatures on the surface of the four-diode module, as calculated in our initial configuration.

During our lab test, the diodes rose from an ambient temperature of 25–27 °C to a maximum of about 54 °C at equilibrium. Our first calculated result is well above the experimental result; we must refine our model.

In the lab, air flow was funneled from the fan to the side of the heat sink with ducting made from copper tape. The bottom and sides of the pin fin array were covered with Kapton tape, so that air could exit the heat sink only from the side opposite the inlet. We modified the simulation geometry to better emulate the lab setup. We added 0.1-mm-thick pieces of insulator material to the bottom and sides of the heat sink, representing the Kapton tape. This new feature restricted the direction of air flow through the heat sink. The air speed and temperature of the external air flow were unchanged from the previous simulation. Using this new configuration, we calculated a maximum temperature on the diode board of 82.1 °C.

Because our result was still well above the measured temperatures, we refined our configuration again to better simulate the experimental setup. We created a box of 0.1-mm-thick insulator enclosing the sides and bottom of the pin-fin array of the heat sink. The simulation was redefined as an internal flow problem, according to SolidWorks Simulation terminology. In this new configuration, the front of the box was defined as the flow inlet with an air flow of 7.2 m/s. The back of the box was defined as the flow outlet at atmospheric pressure (14.7 psi). In this way, we restricted air flow to the pins of the heat sink, recreating the effect of the copper tape funnel used in the lab. Figure 5 shows the direction of air flow in this configuration of the model.

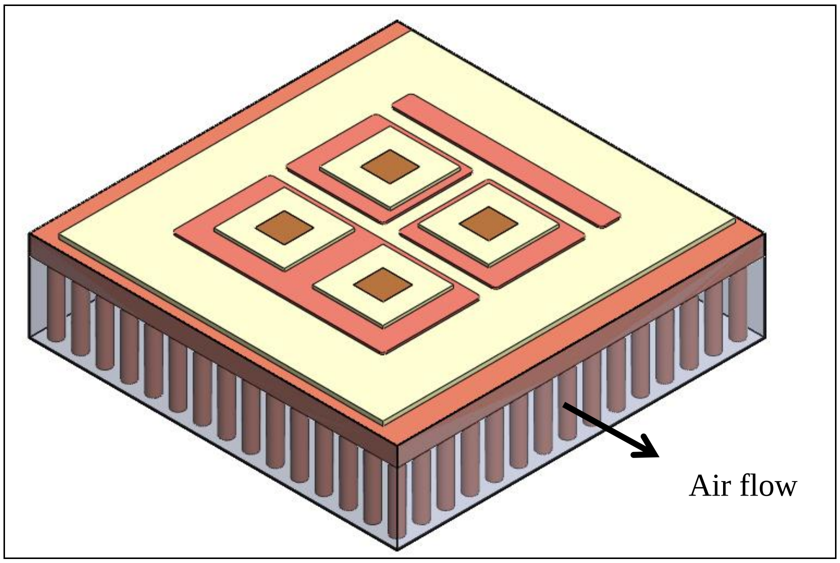

Figure 5. All air flow from the fan is restricted to the heat sink.

From this configuration, we calculated that the maximum temperature on the module was 47.1 °C. Figure 6 is a contour plot of the temperature distribution on the surface of the diode board. We would expect to see lower temperatures on the side of the board nearest the air inlet, and we do see this effect on the left side of our plot, qualitatively confirming our results.

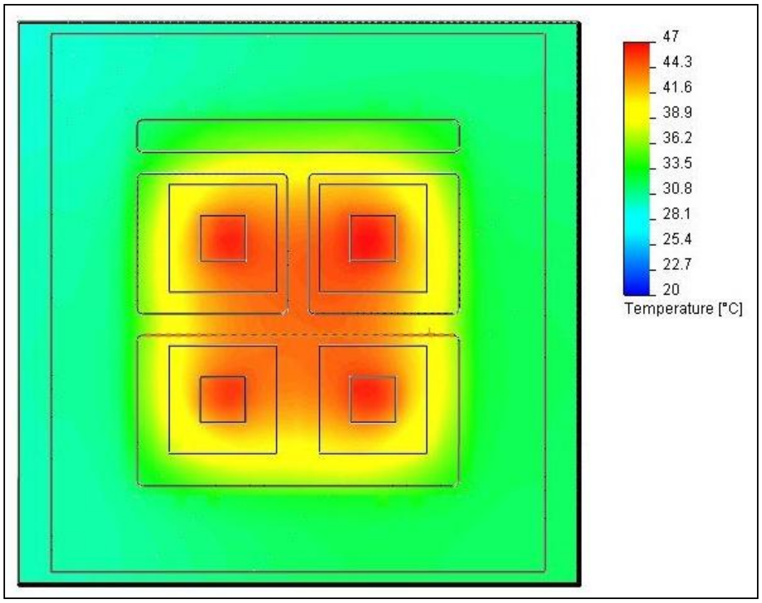

Figure 6. Temperatures on the surface of the 4-diode module, as calculated in our revised configuration.

In our final configuration, we adjusted the ambient temperature in our simulation from 20 °C to 25 °C, the actual ambient temperature in the lab during the circuit test. Other parameters remained the same: air flow was 7.2 m/s and the power loss was 7.6 W per device. Using these parameters, we calculated that the maximum temperature on the diode board was 52.2 °C. Note that increasing the base temperature by 5 °C raised the calculated maximum temperature by approximately the same amount. Figure 7 shows the distribution of temperatures on the surface of the diode bridge in steady state as calculated in our final configuration.

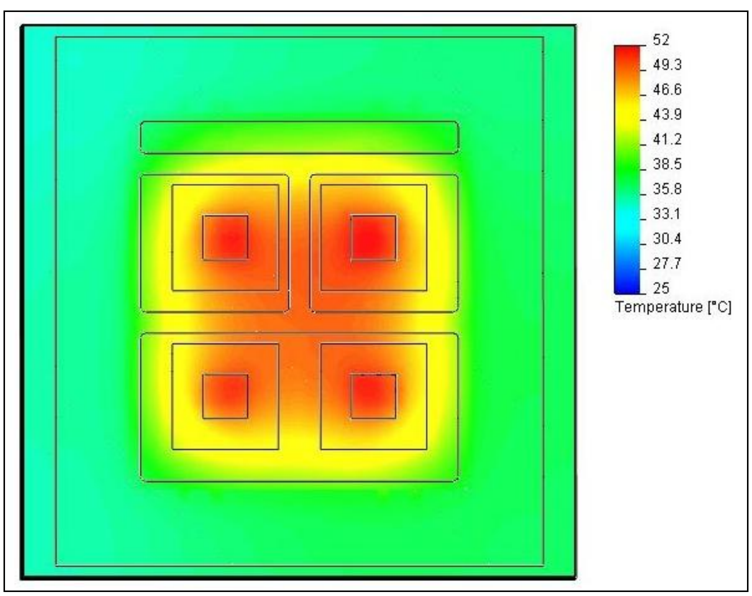

Figure 7. Temperatures on the surface of the four-diode module, as calculated with best geometry and operating parameters.

Compare this plot with the image obtained during the thermal test in our laboratory using a thermal imaging camera, shown in figure 8. This figure shows the bridge circuit at thermal equilibrium, with the diodes at the center of the picture. The maximum temperature in this image is 54.3 °C, which is very close to our calculated maximum temperature. Dimeji Ibitayo and Wes Tipton provided this image, as well as the photographs of the laboratory setup shown earlier.

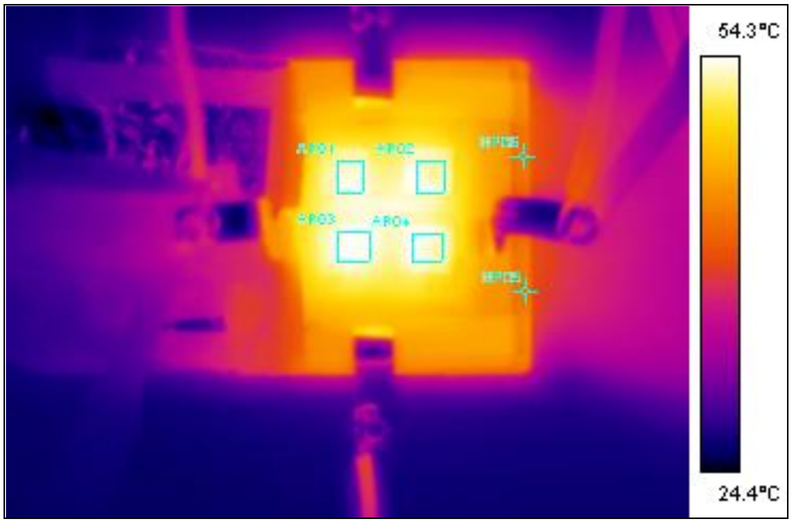

Figure 8. The four-diode board at equilibrium in the laboratory thermal test, as viewed with the thermal imaging camera.

4. Conclusions

We simulated a laboratory test of a high-voltage bridge circuit with four SiC diodes in order to calculate temperatures on the devices during steady-state operation. We performed the simulation in several steps, refining the geometry and operating parameters of the simulation to better reproduce the conditions in the lab. In our final configuration, we calculated that the maximum temperature on the diodes was 52.2 °C. By comparison, the maximum temperature measured with our thermal imaging camera in the laboratory was 54 °C. This result validates our simulation, showing that with careful attention to the details of an electronic device's operation and the geometry of its package, we can calculate steady-state thermal effects with reasonable accuracy. It also implies that if either the operating conditions or module geometry should change, we could predict with some confidence the resulting changes in thermal distribution on the electronic module.

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